TPM Is No Silver Bullet: Pitfalls in Embedded Device Security

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Hi!

David Gstir:

- All things security @ sigma star gmbh
- Security audits of basically everything that runs code
- Engineering and consulting around Linux, embedded systems and security
- Trainings

Intro

- Customers from embedded sector approach us with various security requirements
- TPM comes up more and more lately
- Motivator often compliance with regulations (EU CRA, ISO 62443, ...), but also protecting IP and other reasons
- Encountered some misconceptions (“*But we have a TPM! It’ll solve this!*”) about what a TPM will solve and what not
- This talk is intended to be a guide for *using* TPM in embedded devices
    - Also pentesting such devices that use TPMs ;-)

Trusted Platform Module (TPM)

- Dedicated security chip or software implementation (fTPM)
- Open specification by Trusted Computing Group (TCG)
- Connected via buses like SPI, I2C, LPC
- Commonly used in PCs for long time now - required by Win11
- Rather seldom use on embedded systems
- Latest spec: TPM 2.0

Figure 1: Source: infineon.com

Core TPM Features

- Cryptographic algorithms (ECC, RSA, HMAC, SHA-256, AES, ...)
  - Also some weak ones you should not use anymore!
- CSPRNG
- Multiple Key hierarchies (Platform, Storage, Endorsement, NULL)
- Authorization
- Platform Configuration Registers (PCRs)
- NVRAM storage
- ...

Common Uses of TPMs

Secret Storage

- Used for disk encryption with LUKS/dm-crypt (e.g. via systemd integration)
  - Have disk encryption key bound to TPM
  - Optionally, provide low entropy password (PIN) to unlock
- Also private keys for TLS, VPN, SSH, ...
- Key hierarchies for protected keys which cannot leave TPM
- We can only *use* them by talking to TPM (if proper authorization is done)
- Protect data using internal key (*binding*)
- Small internal storage, but also storage on external media as protected blobs
- A client passes the blob to the TPM to unbind it, which verifies and decrypts it

Measured Boot

- Not to be confused with verified boot where you verify cryptographic signatures of next boot stage
- Boot components (UEFI, bootloader, kernel, etc.) produce measurements on TPM
- Extend (otherwise immutable) *PCRs* which contain cryptographic hash
- Component change results in different PCR hash -> detectable modification
- *Sealing:* TPM keys can be *tied to specific PCR values*, preventing their use if the boot state is altered. Combines nicely with secret storage

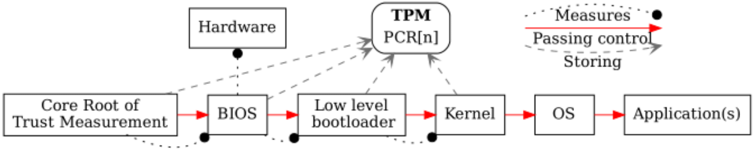

Figure 2: Source: Securing and Hardening Embedded Linux Devices by Marcin Bajer

(Remote) Attestation

- Ensures the device is in a known, secure state before a remote party interacts with it
- Provides a cryptographic proof of the system's boot and configuration state
- Involves an attestation key (AK) and a trust chain to verify the TPM's identity
- Result is a signed *quote* from the TPM, containing the current PCR values and a signature
- Can be used to prove that a device is running a specific, untampered firmware version
- Great overview by Matthew Garrett at *linux.conf.au*[1]

[1] https://www.youtube.com/watch?v=FobfM9S9xSI

TPM on Embedded

- Not common, but possible
- Often Arm-based, so UEFI parts needs some special treatment (measurements!)
- U-Boot implements UEFI and can run UEFI applications[2]
- Verified boot required as well: at least from vendor boot ROM to bootloader
- fTPM can be run as TA via OP-TEE in Arm TrustZone (depends on security/certification requirements)
- Great talk on this by Manuel Traut at *All Systems Go!* 2024[3]

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[2]https://docs.u-boot.org/en/latest/develop/uefi/uefi.html
[3]https://www.youtube.com/watch?app=desktop&v=eJihjE1zb1M

Threat Model: PC vs. Embedded Device

- User wants to protect their data vs. producer wants to protect their IP
- Usually no physical presence (e.g. PIN entry) possible
- Exposure to attacker is trivial: user is potential attacker
- Device is often up 24/7
- More hostile environment: easy tampering with hardware during normal operation
- Longer lifecycles (10+ years)
- Upside: Embedded software more tailored to single use case and thus “easier” to lock down

Pitfalls & Common Threats

Performance & Cold Boot Attacks

- Cryptography on TPM is slow
- Good enough to encrypt/decrypt asym. key, but not suitable for high volume traffic (e.g. symmetric crypto of VPN or TLS)
- When performance is needed CPU has to be used
- TPM will hand decrypted data back to CPU
- Exposes secrets to main memory
- Dedicated measures against cold boot attacks and similar attack vectors are needed!

Runtime Integrity Protection

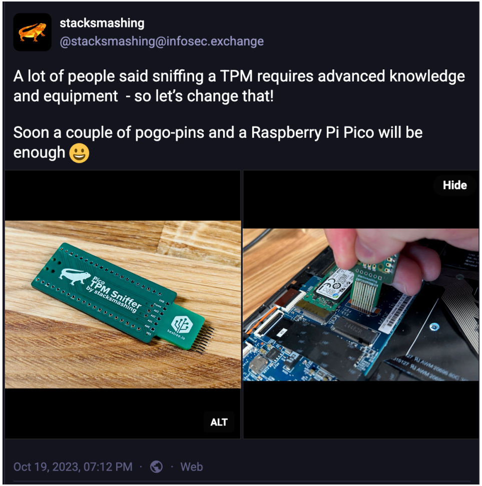
- Measured boot and verified boot protect boot chain only
- Runtime modification often not covered (no PCR changes)
- Code execution vulnerability can result in access to TPM
- TPM alone cannot solve this
- Hardening for disk encryption: seal key to PCRs and modify a PCR after disk is mounted
- Additional measures:
  - limited privileges per process
  - FS permissions
  - SELinux
  - IMA/EVM
  - Unique keys per device

Direct Physical Attacks

- Physical chip can be attacked using variety of physical attacks (tampering, side-channel, fault injection)
- Measures against this depend on individual chip
- Often very limited protection (chip coating, tamper evidence)
- Often just compliance theater
- Have a look at FIPS 140-2 or ISO/IEC 19790 security level certification of your chip
- But there are easier ways...

Bus Snooping

- Attach probes to physical bus between TPM and CPU to read messages
- Is easier than it sounds[4]
- TPM mitigations: session-based command and response parameter encryption
- Multiple modes: HMAC-based can include PCRs
- Client needs to opt in to these, otherwise plaintext comm is used!
- Not all TPM clients do
- systemd's TPM+dm-crypt integration does this already



[4]https://github.com/nccgroup/TPMGenie

Active Interposer Attacks

- Can launch man-in-the-middle attacks between CPU and TPM
- If encrypted & authenticated sessions are properly used, this can be partially mitigated
- E.g. systemd's dm-crypt integration places Storage Root Key (SRK) metadata into LUKS header[5]
  - MitM attacker will not have access to private SRK
  - But there are some caveats like this metadata has to be signed and verified
- Problem still: interposer can reset TPM and rebuild PCRs as needed
- Kernel recently (6.10) gained ability to detect this
- Still requires userspace to do full attestation of TPM's EK certificate
- See talk by James Bottomley at FOSDEM 2025[6]

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[5] https://github.com/systemd/systemd/issues/22637

[6] https://fosdem.org/2025/schedule/event/fosdem-2025-4827-recent-tpm-security-enhancements-to-the-linux-kernel/

TPM Hardware & Firmware Flaws

- TPM firmware can contain flaws
- Has happened before with ST chips: see TPM-FAIL (CVE-2019-16863)[7]
- When fixable by update, you as vendor are responsible to ship the update!
- Hardware flaws often impossible to fix by update
- Also happened before: ROCA vuln. (CVE-2017-15361) in Infineon chips[8]
- Measures against such flaws are limited
- Additional hardening of whole system (OS, backend) can help (unique key per device, mitigate code execution flaws)

[7] https://tpm.fail/tpmfail.pdf
[8] https://blog.cr.yp.to/20171105-infineon.html

Software-based TPM Issues

- fTPM removes bus snooping issue
- Still vulnerable to side-channel, timing leaks and similar flaws.
- E.g. faulTPM vulnerability[9]
- Adds more things to maintain and keep secure
- fTPM in TrustZone:
  - fTPM code needs to be kept up-to-date
  - TrustZones have flaws as well: e.g. memory flaws[10]
- fTPM in OP-TEE:
  - requires secure storage layer itself
  - requires some form of hardware support (eMMC RPMB)
  - eMMC RPMB: don't hardcode key in your code

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[9] https://arxiv.org/abs/2304.14717
[10] https://link.springer.com/article/10.1007/s11416-021-00413-y

Alternatives to TPMs

- Vendor-specific solutions like NXP CAAM
- Custom solutions based on Arm TrustZone or similar TEE
- Dedicated security chips e.g. Apples Secure Enclave
- Hardware-security modules (HSMs)

Summary

- TPM is definitely an options for embedded devices
- It enables reuse of existing features we use on PCs (e.g. disk encryption)
- Threat model is different
- TPM alone cannot solve everything
- Additional security measures need to be added

FIN

Thank you!

Questions, Comments?

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